

## Exotic in Leptonic Machines

KAI ZHU

*Institute of High Energy Physics, Beijing, China*

Selected topics of exotics in leptonic machines are presented, including recent discovery of abnormal structures around the  $p\bar{p}$  threshold and new information of the XYZ (charmonium-like) states.

PRESENTED AT

Flavor Physics & CP Violation 2014 (FPCP 2014)  
Marseille, France, May 25–30, 2014

# 1 Introduction

After Higgs, the last missing block of the standard model (SM), has been discovered experimentally, more physicists transfer their interest to new physics beyond the SM. However, even within the SM model, there are still some predictions have not been confirmed or validated. The quantum chromodynamics (QCD) predicts that there are more hadronic states than the usual mesons ( $q\bar{q}$  states) and baryons ( $qqq$  states). There should be bound gluons (glueball),  $q\bar{q}$ -pair with an excited gluon (hybrids), multi-quark color singlet states such as:  $q\bar{q}q\bar{q}$  (tetra-quark and molecular),  $q\bar{q}q\bar{q}q$  (penta-quark),  $q\bar{q}q\bar{q}q\bar{q}$  (six-quark and baryonium) and *et al.*. However, none of these exotic states have really been established or ruled out experimentally.

Leptonic machines, so called charm-factories or B-factories, due to their relative high luminosities and clean backgrounds, provide idea places to study these exotic states. In this proceeding I will present some new the discoveries and measurements attributed to BESIII, CLEOc, Belle and BarBar. The main body will be divided into two parts, one is for the light-hadronic spectrum and the other one is for heavier charmonium-like states. The first part contains the recently found structures near  $p\bar{p}$  threshold such as  $X(p\bar{p})$ ,  $X(1835)$ ,  $X(1840)$ ,  $X(1870)$ ,  $X(1810)$ . The second part contains the very recent progresses on the XYZ (charmonium-like) states, such as new production mode, discoveries of new resonance, updating previous measurements with larger statistics, *et al.*. I must apologize I cannot include all the interesting topics in this field.

## 2 Structures near the $p\bar{p}$ threshold

An anomalous enhancement near the  $p\bar{p}$  mass-threshold was first observed by the BESII experiment in the  $J/\psi$  radiative decay process  $J/\psi \rightarrow \gamma p\bar{p}$  [1] and was confirmed by the BESIII [2] and CLEO-c [3] experiments. Recently, a partial wave analysis (PWA) in the radiative decay  $J/\psi \rightarrow \gamma p\bar{p}$  is applied [4], the  $J^{PC}$  quantum numbers of the  $p\bar{p}$  mass-threshold enhancement is determined to be  $0^{-+}$ , with peak mass  $M = 1832_{-5}^{+19}(\text{stat})_{-17}^{+18}(\text{syst}) \pm 19(\text{model})\text{MeV}/c^2$  below the threshold and total width  $\Gamma = 13 \pm 39(\text{stat})_{-13}^{+10}(\text{syst}) \pm 4(\text{model})\text{MeV}/c^2$  at the 90% C.L. The product of branching fractions is  $Br[J/\psi \rightarrow \gamma X(p\bar{p})]Br[X(p\bar{p}) \rightarrow p\bar{p}] = [9.0_{-1.1}^{+0.4}(\text{stat})_{-5.0}^{+1.5}(\text{sys}) \pm 2.3(\text{model})] \times 10^{-5}$ . Fig. 1(a) shows a comparison between data and PWA fit projection on the  $p\bar{p}$  invariant mass; here, the black dots with error bars are data, the solid histograms show the PWA total projection, and the dashed, dotted, dash-dotted, and dash-dot-dotted lines show the contributions of the  $X(p\bar{p})$ ,  $0^{++}$  phase space,  $f_0(2100)$  and  $f_2(1910)$ , respectively.

However, such near  $p\bar{p}$  mass-threshold structure has not been observed in  $p\bar{p}$  cross section measurements, in B-meson decays [5, 6], in radiative  $\psi(3686)$  or  $\Upsilon$  decays to

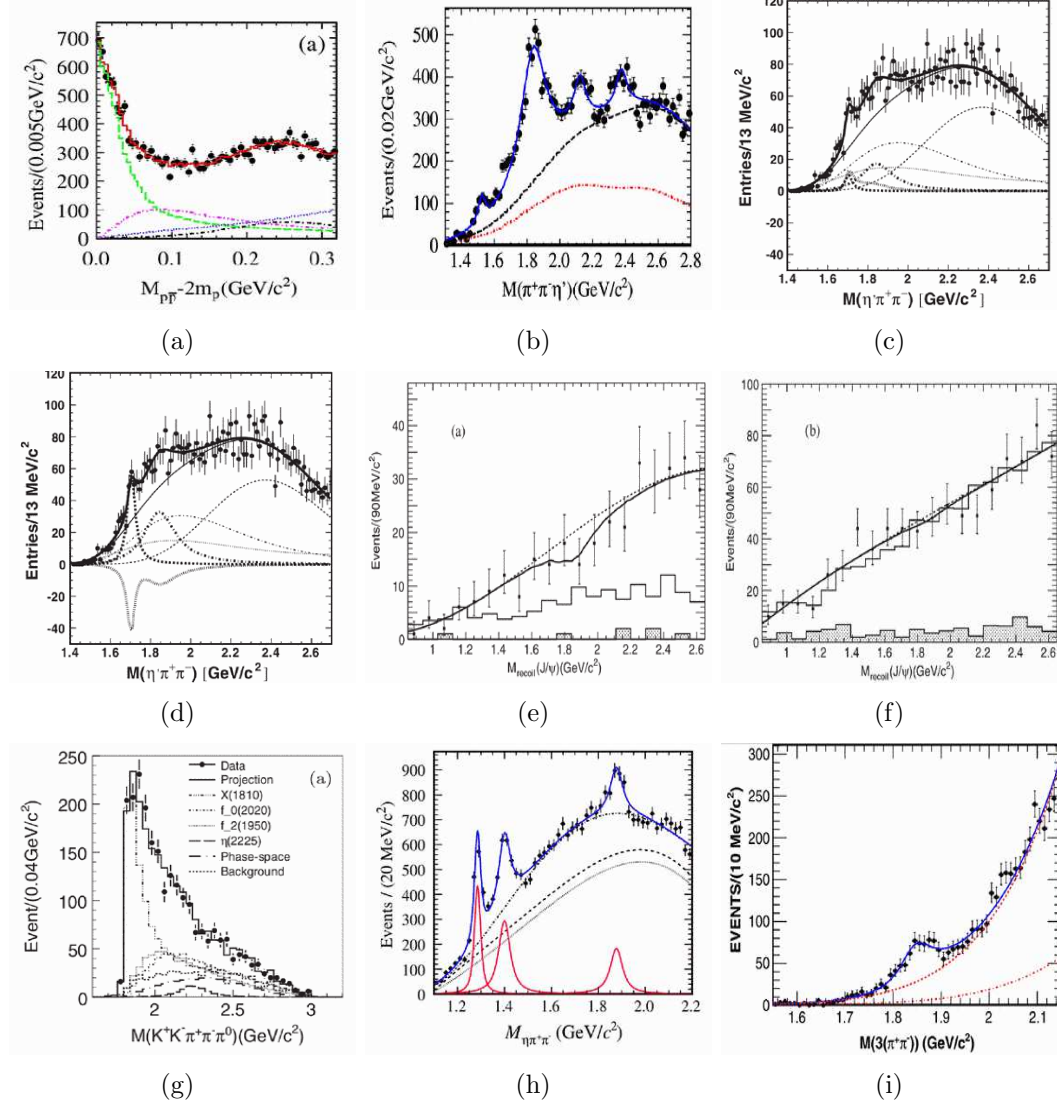


Figure 1: Structures near the  $p\bar{p}$  threshold via different processes. (a):  $J/\psi \rightarrow \gamma p\bar{p}$ ; (b):  $J/\psi \rightarrow \gamma \pi^+\pi^-\eta'$ ; (c):  $\gamma\gamma \rightarrow \pi^+\pi^-\eta'$  (constructive); (d):  $\gamma\gamma \rightarrow \pi^+\pi^-\eta'$  (destructive); (e):  $e^+e^- \rightarrow J/\psi + X(1835)$  ( $e^+e^-$  mode); (f):  $e^+e^- \rightarrow J/\psi + X(1835)$  ( $\mu\mu$  mode); (g):  $J/\psi \rightarrow \gamma\omega\phi$ ; (h):  $J/\psi \rightarrow \omega a_0^\pm(980)\pi^\mp$ ; (i):  $J/\psi \rightarrow \gamma 3(\pi^+\pi^-)$ .

$p\bar{p}$  [7,8], or in  $J/\psi \rightarrow \omega p\bar{p}$  decays [9,10]. These non-observations exclude the attribution of the mass-threshold enhancement to a pure final state interaction (FSR) [11–16].

Inspired by the anomalous  $p\bar{p}$  invariant mass threshold enhancement,  $J/\psi \rightarrow \gamma \pi^+\pi^-\eta'$  is searched and a  $\pi^+\pi^-\eta'$  resonance, the  $X(1835)$ , was observed by the BESII experiment [17]. Recently, with a larger  $J/\psi$  sample,  $(225.2 \pm 2.8) \times 10^6$  events registered in the BESIII detector,  $J/\psi \rightarrow \gamma \pi^+\pi^-\eta'$  is studied using two  $\eta'$  decay modes:

$\eta' \rightarrow \pi^+\pi^-\eta$  and  $\eta' \rightarrow \gamma\rho^0$  [18]. The  $X(1835)$  is confirmed with a statistical significance larger than 20 standard deviations, as well as two new structures, the  $X(2120)$  and  $X(2370)$ , are observed in the  $\pi^+\pi^-\eta'$  invariant-mass spectrum with statistical significances larger than  $7.2\sigma$  and  $6.4\sigma$ , respectively. Fig. 1(b) shows the mass spectrum fitted with four resonances; here, the dash-dotted line is contributions of non- $\eta'$  events and the  $\pi^0\pi^+\pi^-\eta'$  background for two  $\eta'$  decay modes, and the dashed line is contributions of the total background and non-resonant  $\pi^+\pi^-\eta'$  process. The masses and widths of  $X(1835)$  are measured to be  $M = 1836.5 \pm 3.0(stat)_{-2.1}^{+5.6}(syst)$  MeV/ $c^2$ ,  $\Gamma = 190 \pm 9(stat)_{-36}^{+38}(syst)$  MeV/ $c^2$ . The product branching ratios is  $Br[J/\psi \rightarrow \gamma X(1835)] \cdot Br[X(1835) \rightarrow \pi^+\pi^-\eta'] = [2.87 \pm 0.09(stat)_{-0.52}^{+0.49}(syst)] \times 10^{-4}$ , and the angular distribution of the radiative photon is consistent with a pseudo-scalar assignment. Another attempt to search  $X(1835)$  via  $\gamma\gamma \rightarrow \pi^+\pi^-\eta'$  is implemented by Belle [19], in which the interference between  $X(1835)$  and  $\eta(1760)$  has been considered, but no strong evidence was found. Figs. 1(c) and 1(d) show the constructive and destructive interference respectively. Inspired by a C-even glueball can be studied in the process  $e^+e^- \rightarrow \gamma^* \rightarrow HG$  [20], where  $H$  denotes a  $c\bar{c}$  quark pair or a charmonium state and  $G$  is a glueball,  $X(1835)$  is also searched via  $e^+e^- \rightarrow J/\psi + x(1835)$  at  $\sqrt{s} \approx 10.6\text{GeV}$  [21]. Figs. 1(e) and 1(f) show no significant evidence is found to support the hypothesis of the  $X(1835)$  as a glueball produced in association with a  $J/\psi$ .

An anomalous near-threshold enhancement in the  $\omega\phi$  invariant-mass spectrum in the process  $J/\psi \rightarrow \gamma\omega\phi$  was reported by the BESII experiment [22], that was assumed to an existence of a resonance, *i.e.* the  $X(1810)$ . With the new  $J/\psi$  event sample accumulated with the BESIII detector, the process is re-studied recently [23], and a partial wave analysis with a tensor co-variant amplitude is performed. The projection on the invariant mass of  $\omega\phi$  is shown in Fig. 1(g). The spin-parity of the  $X(1810)$  is determined to be  $0^{++}$ . Its mass and width are measured to be  $M = 1795 \pm 7(stat)_{-5}^{+13}(syst) \pm 19(mode)\text{MeV}/c^2$  and  $\Gamma = 95 \pm 10(stat)_{-34}^{+21}(syst) \pm 75(mode)\text{MeV}/c^2$ , respectively. And the product branching fraction is determined to be  $Br[J/\psi \rightarrow \gamma X(1810)] \times Br[X(1810) \rightarrow \omega\phi] = [2.00 \pm 0.08(stat)_{-1.00}^{+0.45}(syst) \pm 1.30(mod)] \times 10^{-4}$ .

Using the same data sample as mentioned above, BESIII collaboration reported the observation of a new process  $J/\psi \rightarrow \omega X(1870)$  [24] with a statistical significance of  $7.2\sigma$ , in which  $X(1870)$  decays to  $a_0^\pm(980)\pi^\mp$ . Fitting to  $\eta\pi^+\pi^-$  mass spectrum yields the mass, width and product branching fraction are  $M = 1877.3 \pm 6.3(stat)_{-7.4}^{+3.4}(syst)\text{MeV}/c^2$ ,  $\Gamma = 57 \pm 12(stat)_{-4}^{+19}(syst)\text{MeV}/c^2$ , and  $Br(J/\psi \rightarrow \omega X) \times Br(X \rightarrow a_0^\pm(980)\pi^\mp) \times Br(a_0^\pm(980) \rightarrow \eta\pi^\pm) = [1.50 \pm 0.26(stat)_{-0.36}^{+0.72}(syst)] \times 10^{-4}$ . Fig. 1(h) shows the results of the fit to the  $M(\eta\pi^+\pi^-)$  mass distribution for the events with either the  $\eta\pi^+$  or  $\eta\pi^-$  in the  $a_0(980)$  mass window. The dotted curve shows the contribution of non- $\omega$  and/or non- $a_0(980)$  background, the dashed line also includes the contribution from  $J/\psi \rightarrow b_1(1235)a_0(980)$ , and the dot-dashed curve indicates

the total background with the non-resonant  $J/\psi \rightarrow \omega a_0^\pm(980)\pi^\mp$  included.  $\chi^2/d.o.f.$  is 1.27 for this fit.

BESIII also analyzed the decay  $J/\psi \rightarrow \gamma 3(\pi^+\pi^-)$  with the same  $J/\psi$  sample [25]. A structure at  $1.84\text{GeV}/c^2$  is observed in the  $3(\pi^+\pi^-)$  invariant mass spectrum with a statistical significance of  $7.6\sigma$ . The mass and width are measured to be  $M = 1842.2 \pm 4.2_{-2.6}^{+7.1}\text{MeV}/c^2$  and  $\Gamma = 83 \pm 14 \pm 11\text{MeV}$ . The product branching fraction is determined to be  $Br[J/\psi \rightarrow \gamma X(1840)] \times Br[X(1840) \rightarrow 3(\pi^+\pi^-)] = (2.44 \pm 0.36_{-0.74}^{+0.60}) \times 10^{-5}$ . Fig. 1(i) shows the fit of the mass spectrum of  $3(\pi^+\pi^-)$ . The dots with error bars are data; the solid line is the fit result. The dashed line represents all the backgrounds, including the background events from  $J/\psi \rightarrow \pi^0 3(\pi^+\pi^-)$  (represented by the dashed-dotted line, fixed in the fit) and a third-order polynomial representing other backgrounds.

Fig. 2 shows the comparison of the masses and widths of all the structures near threshold of  $p\bar{p}$  mentioned before. Four of the five are from  $J/\psi$  radiative decays. Although it's well known that  $J/\psi$ 's radiative decays favor glue-balls, we are reasonably sure that  $X(1835)$  would not be a glueball since it has not been observed in a production associated with a  $J/\psi$ . We also know that  $X(p\bar{p})$  is not found in  $\psi'$  radiative decay and  $J/\psi \rightarrow \omega p\bar{p}$ , then it does not likely from a pure FSI. A number of theoretical speculations have been proposed to interpret the nature of the structure near the  $p\bar{p}$  threshold structure [11–16, 26–28]. Among them, the most intriguing suggestion is that it is due to a  $p\bar{p}$  bound state, also called baryonium [26–28], a predicted state with a long history and been searched by many experiments [29]. However, all the information we obtained till now is too limited to draw a final conclusion. We even don't know whether all, or part of, the enhancements near the  $p\bar{p}$  threshold are related to a same source still. Further studies are surely needed; among these, spin-parity determination, precise measurements of masses, widths, and branching ratios are especially important.

### 3 XYZ particles

$X(3872)$  was first observed in the process  $B \rightarrow K(\pi^+\pi^- J/\psi)$  by Belle [30], its mass is close to the  $D^0 D^{*0}$  threshold and width is very narrow. CDF [31] and LHCb [32] determined its  $J^{PC}$  is  $1^{++}$ . The partial width measurement shows that it takes a 50% chance to decay via open-charm channel and at the  $O(\%)$  via charmonium. There are many proposed interpretation for its nature since its discovery, such as  $\chi_{c1}(2P)$ ,  $D^0 D^{*0}$  molecule, hybrid of meson and glue-ball, and tetra-quark states, *et al.*. However none of them is totally satisfactory and the nature of  $X(3872)$  is still a mystery.  $X(3872)$  has only been found in the pp collision and B decays, until recently BESIII reported a new production mode of  $e^+e^- \rightarrow \gamma(\pi^+\pi^- J/\psi)$  [33], with data samples collected with the BESIII detector at center-of-mass energies from 4.009

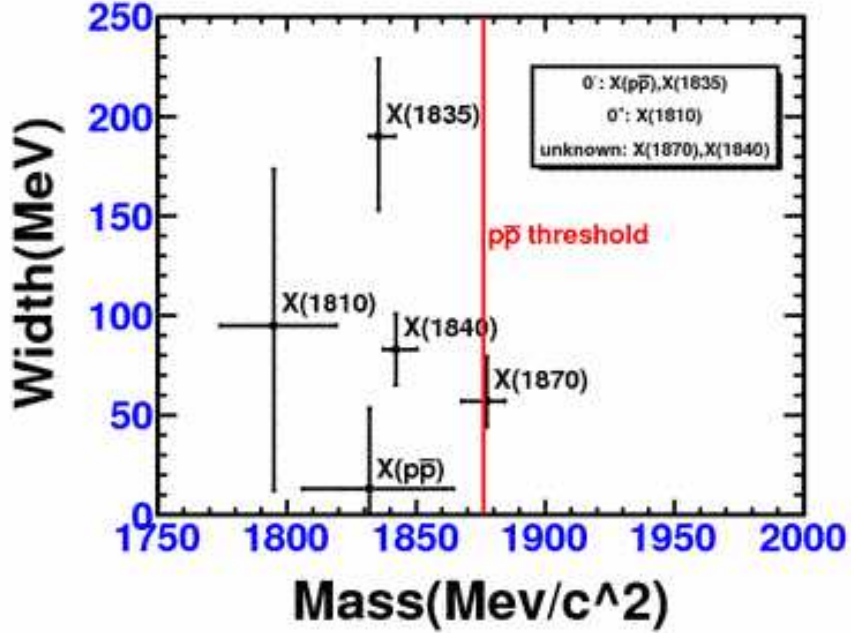


Figure 2: Comparison of masses, widths and quantum numbers of the structures near the  $p\bar{p}$  threshold.

to 4.420 GeV. Figs. 3 show the  $\pi^+\pi^-J/\psi$  invariant mass distributions at four energies. The measurements results are consistent with expectations for the radiative transition process  $Y(4260) \rightarrow \gamma X(3872)$ .

Many, maybe too many, Y states have been reported in last decade, such as  $Y(4008)$ ,  $Y(4260)$ ,  $Y(4360)$ ,  $Y(4630)$ , and  $Y(4660)$ , *et al.*. Most of them are found in ISR processes, so they are vector states, where the total number of them is surely beyond the theoretical prediction of charmonium states at this energy region by the potential model. One interesting thing is these Y states are only discovered in  $\pi^+\pi^-J/\psi$  [34, 35],  $\pi^+\pi^-\psi(2S)$  [36], and  $\Lambda_c^+\Lambda_c^-$  [37] modes, but there is no sign of  $Y \rightarrow D^{(*)}D^{(*)}$  [38–40] modes. Recently, Babar and Belle have updated their studies of Y states with larger statistics. Figs. 4(a) and 4(b) show the cross sections of  $\pi^+\pi^-J/\psi$  final states from Babar [41] with  $454fb^{-1}$  and Belle [42] with  $967fb^{-1}$  electron-positron colliding events via ISR process. In Belle's report, still two resonances  $Y(4008)$  and  $Y(4260)$  are observed, just agrees with Belle's previous results. In Babar's result, significant  $Y(4260)$  is found, but  $Y(4008)$  is not confirmed. But from Fig. 4(a), there are some events accumulated at around the 4.008 GeV, so it may due to different fit methods used by Babar and Belle. For the  $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-\psi(2S)$ , Babar updated it with  $520pb^{-1}$  [43] and Belle with  $980fb^{-1}$ . Figs. 4(c) shows the

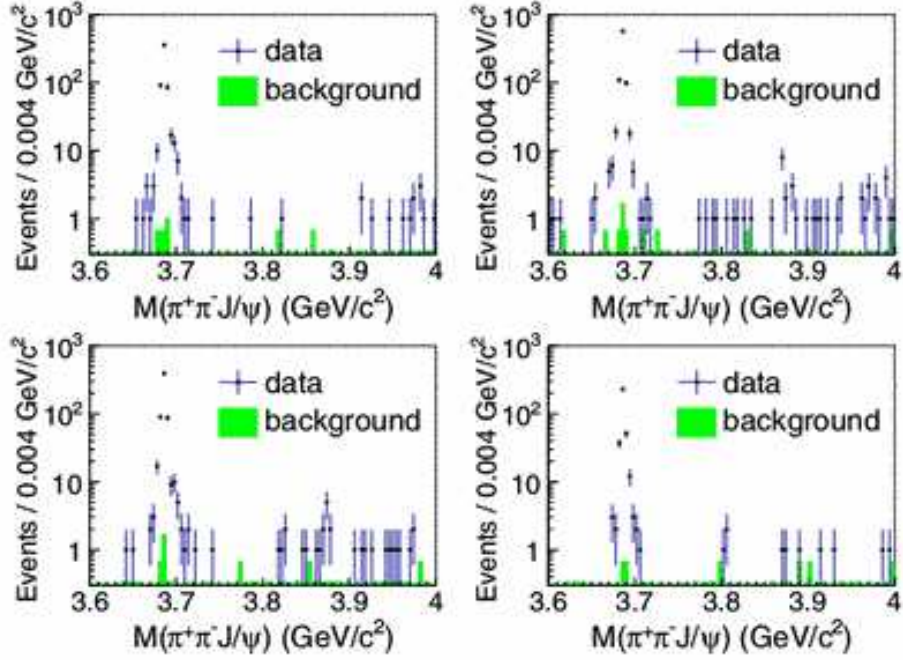


Figure 3: The  $\pi^+\pi^-J/\psi$  invariant mass distributions at  $\sqrt{s} = 4.009$  (top left), 4.229 (top right), 4.260 (bottom left), and 4.360 GeV (bottom right). Dots with error bars are data, the green shaded histograms are normalized  $J/\psi$  sideband events.

cross section of  $\pi^+\pi^-\psi(2S)$  final states from Babar, and it is fitted with  $Y(4360)$  and  $Y(4660)$  two resonances, and two solutions are found. As a preliminary result, Belle fitted its data with  $Y(4260)$ ,  $Y(4360)$  and  $Y(4660)$ , it turns out the significance of  $Y(4260)$  is only  $2.1\sigma$ , but its effect on the others is large.

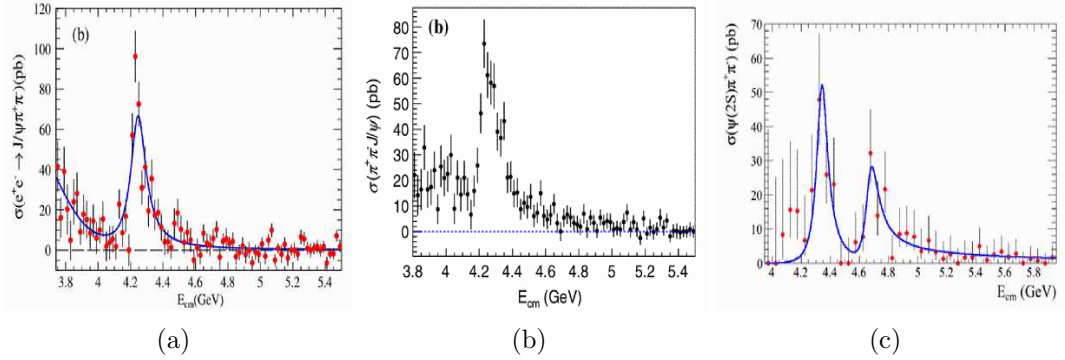


Figure 4: Cross section of  $\pi^+\pi^-J/\psi$  and  $\pi^+\pi^-\psi(2S)$  final states. (a)  $\pi^+\pi^-J/\psi$  mode from Babar; (b)  $\pi^+\pi^-J/\psi$  mode from Belle; (c)  $\pi^+\pi^-\psi(2S)$  mode from Babar.

There are also other attempts to study the Y states via  $\pi^+\pi^-h_c$  [44, 45] and  $\omega\chi_{cJ}$  final states. Fig. 5(a) shows an individual work based on the combined BESIII and CLEO-c data [46], where a narrow  $Y(4220)$  and a wide  $Y(4290)$  states are used to describe the structures. Fig. 5(b) shows a cross section distribution of  $\omega\chi_{c0}$  as a preliminary result of BESIII, and no signal of  $\omega\chi_{c1}$  and  $\omega\chi_{c2}$  are found disfavors  $Y(4260)$  is a  $\omega\chi_{c1}$  module.

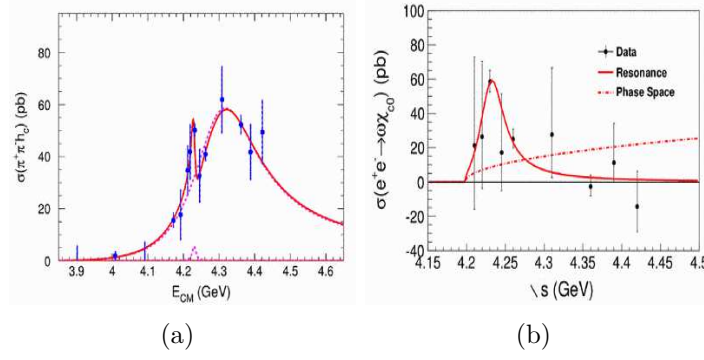


Figure 5: (a) Fit based on the combined BESIII and CLEO-c data; (b) Cross section of  $\omega\chi_{c0}$ .

A charged Z state named  $Z_c(3900)$  is observed by BESIII [47] and Belle [42] via  $\pi^\pm J/\psi$ , and confirmed with CLEO-c's data [48]. The measured mass, width, number of events and significance of the three experiments are shown in Table. 1, the shapes of the  $M_{max}(\pi^\pm J/\psi)$  are shown in Fig. 6. Analysis shows  $Z_c(3900)$  is strongly coupled to  $c\bar{c}$  as well as has electric charge, that indicates it at least a 4-quarks state. Many interpretations are proposed, such as  $DD^*$  module, tetra-quark state, Cusp, and threshold effect, *et al.*, but none of them is a satisfied explanation yet.

Exp.	$M(MeV)$	$\Gamma(MeV)$	Num. of Evt.	significance
BESIII	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	$307 \pm 48$	$> 8\sigma$
Belle	$3894.5 \pm 6.6 \pm 4.5$	$63 \pm 24 \pm 26$	$159 \pm 49$	$> 5.2\sigma$
CLEO-c data	$3885 \pm 5 \pm 1$	$34 \pm 12 \pm 4$	$81 \pm 20$	$6.1\sigma$

Table 1: Mass, width, number of events and significance of the  $Z_c(3900)$  from three experiments.

Other  $Z_c$  production modes or partners are searched at BESIII with  $\pi^\pm(D\bar{D}^*)^\mp$  [49],  $\pi^\pm(D^*\bar{D}^*)^\mp$  [50],  $\pi^+\pi^-h_c$  [45], and  $\pi^0\pi^0h_c$ . The so called  $Z_c(3885)$ ,  $Z_c(4025)$ , charged  $Z_c(4020)$  and neutral  $Z_c(4020)$  are found; their mass and width are listed in Table 2, and their shapes are shown in Fig. 7. Belle observed  $Z_c(4030)$  via  $B \rightarrow \psi' K \pi^-$



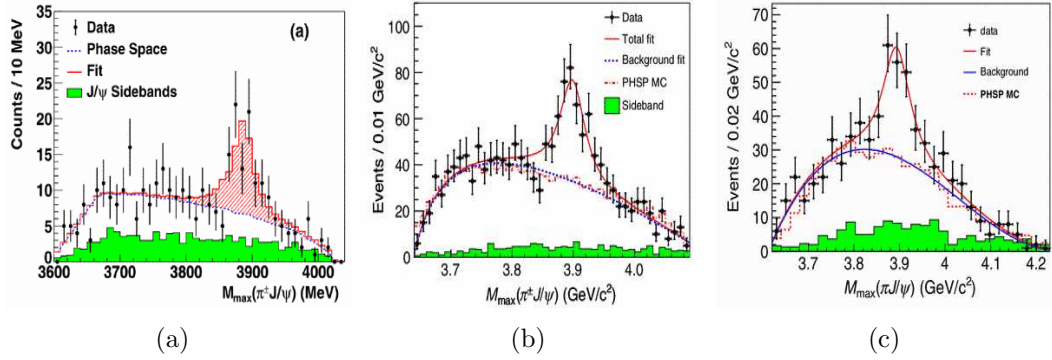


Figure 6: Shapes of  $Z_c(3900)$ ,  $M_{max}(\pi^\pm J/\psi)$  from (a) CLEO-c data, (b) BESIII; (c) Belle.

( $K = K_s^0 \text{ or } K^+$ ) [51], and it's confirmed by LHCb via  $B^0 \rightarrow \psi' \pi K^+$  [52], as well as its  $J^P$  is determined as  $1^+$ .

states	$M(\text{MeV})$	$\Gamma(\text{MeV})$
$Z_c(3885)$	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
$Z_c(4025)$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$
$Z_c^\pm(4020)$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$
$Z_c^0(4020)$	$4023.6 \pm 2.2 \pm 3.9$	fixed to $\Gamma(Z_c^\pm(4020))$

Table 2: Mass and width of other  $Z_c$  states.

In order to search  $Z_{cs}$ , Belle updated its previous  $K^+ K^- J/\psi$  measurement to a Dalitz Plot analysis [53], no evident structure is found in  $K^\pm J/\psi$  mass distribution under current statistics.

Belle has observed  $Z_b(10610)$  and  $Z_b(10650)$  in  $\pi^+ \pi^- \Upsilon(nS)$  [54,55],  $\pi^+ \pi^- h_b(mP)$  [56] and  $[B\bar{B}^*]^\pm \pi^\mp$  [57] final states. Their possible relations to  $Z_c$  states are displayed in Fig. 8, here we assume  $Z_c(3900)$  and  $Z_c(3885)$  are a same state  $Z_c$ , and  $Z_c(4020)$  and  $Z_c(4025)$  are a same state  $Z'_c$ . From this plot, more excited states or production mode of  $Z$  particles are expected.

## 4 summary

Leptonic machines produce exotics. These particles are unexpected, weird and strange, while also tantalizing, charming and interesting, and only very limited topics of these exotics is covered in this proceeding. Some abnormal structures near  $p\bar{p}$  threshold are observed with similar masses, the significances of these signals are large. However,

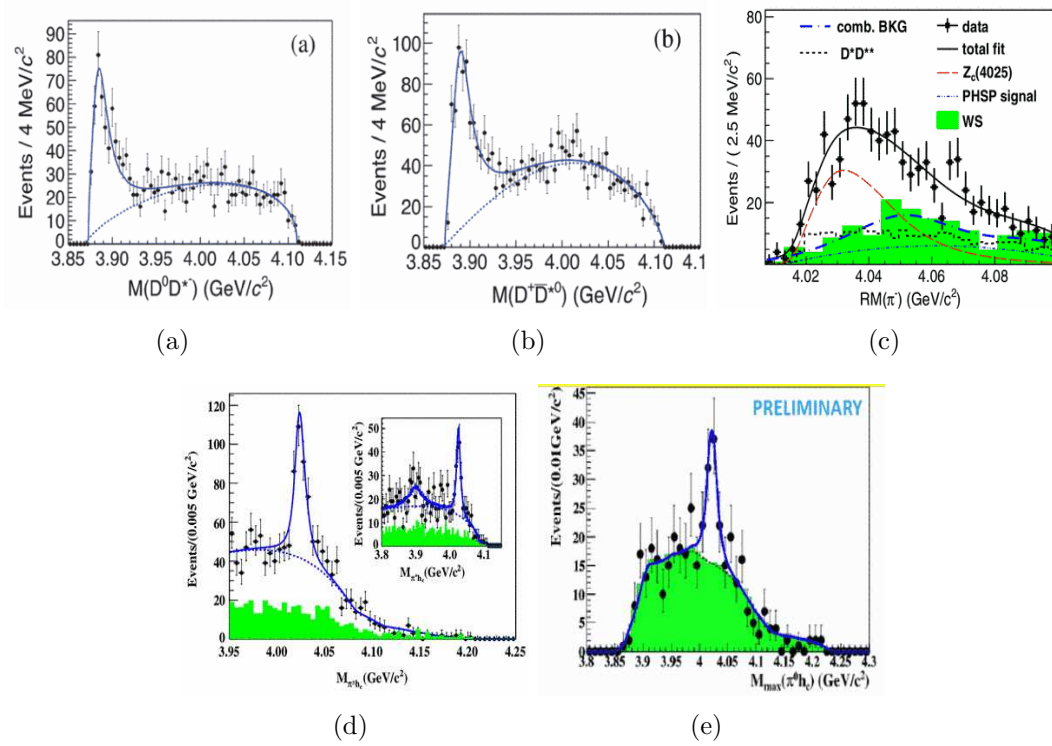


Figure 7: Shapes of (a)(b)  $Z_c(3885)$ ; (c)  $Z_c(4025)$ ; (d)  $Z_c^\pm(4020)$ , (e)  $Z_c^0(4020)$ .

there are many questions need answer. Are they from a same source? Are they baryonia, glueball or hybrid? For some cases, PWA is needed to determine the spin and parity. Search via more decay modes will help to reveal the veil. Lots of and very fast progresses in XYZ studies with  $e^+e^-$  experiments in recent years, only some new measurements are reviewed in this proceeding. It includes: a new production mode of  $X(3872)$ ; some new information on the Y states from Babar, Belle and BESIII. Till now, most of the Y states are charmonium related, more decays modes of them worthy checking. There are also contradictive conclusions from different experiment collaborations due to limited statistics.  $Z_c(3900)$ , the first confirmed at least four-quarks state, and its partners has been presented also. Their nature are still unknown. A systematic study of its quantum number, decay modes, excited states, comparison with their beauty-counterparts is crucial to achieve a satisfactory explanation. With more upcoming data of the leptonic machines, an exciting future is expected.

## ACKNOWLEDGEMENTS

I am grateful to the FPCP2014 committee for the organization of this nice conference.

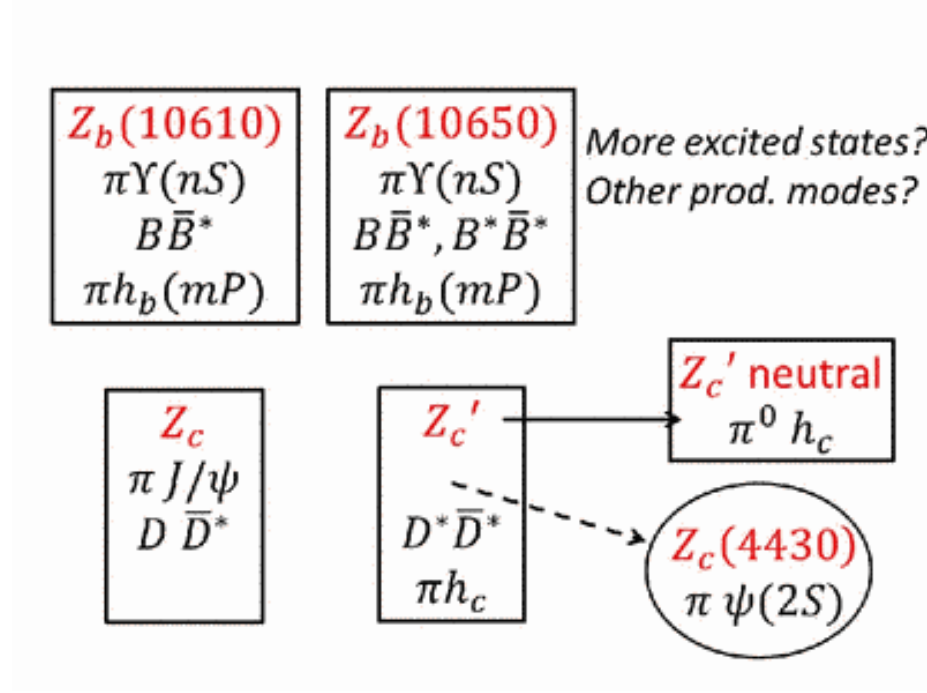


Figure 8: Comparison of production modes of  $Z_c$  and  $Z_b$  states.

## References

- [1] J. Z. Bai *et al.* [BES Collaboration], Phys. Rev. Lett. **91**, 022001 (2003) [hep-ex/0303006].
- [2] M. Ablikim *et al.* [BESIII Collaboration], Chinese Physics **C34**, 421 (2009)
- [3] J. P. Alexander *et al.* [CLEO Collaboration], Phys. Rev. D **82**, 092002 (2010) [arXiv:1007.2886 [hep-ex]].
- [4] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **108**, 112003 (2012) [arXiv:1112.0942 [hep-ex]].
- [5] S. Jin, Int. J. Mod. Phys. A **20**, 5145 (2005).
- [6] M. Z. Wang *et al.* [Belle Collaboration], Phys. Rev. Lett. **92**, 131801 (2004) [hep-ex/0310018].
- [7] M. Ablikim *et al.* [BES Collaboration], Phys. Rev. Lett. **99**, 011802 (2007) [hep-ex/0612016].
- [8] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. D **83**, 032001 (2011) [arXiv:1009.6224 [hep-ex]].

- [9] M. Ablikim *et al.* [BES Collaboration], Eur. Phys. J. C **53**, 15 (2008) [arXiv:0710.5369 [hep-ex]].
- [10] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **87**, no. 11, 112004 (2013) [arXiv:1303.3108 [hep-ex]].
- [11] A. Sibirtsev, J. Haidenbauer, S. Krewald, U. -G. Meissner and A. W. Thomas, Phys. Rev. D **71**, 054010 (2005) [hep-ph/0411386].
- [12] G. Y. Chen, H. R. Dong and J. P. Ma, Phys. Lett. B **692**, 136 (2010) [arXiv:1004.5174 [hep-ph]].
- [13] B. S. Zou and H. C. Chiang, Phys. Rev. D **69**, 034004 (2004) [hep-ph/0309273].
- [14] X. -H. Liu, Y. -J. Zhang and Q. Zhao, Phys. Rev. D **80**, 034032 (2009) [arXiv:0903.1427 [hep-ph]].
- [15] N. Kochelev and D. -P. Min, Phys. Lett. B **633**, 283 (2006) [hep-ph/0508288].
- [16] T. Huang and S. -L. Zhu, Phys. Rev. D **73**, 014023 (2006) [hep-ph/0511153].
- [17] M. Ablikim *et al.* [BES Collaboration], Phys. Rev. Lett. **95**, 262001 (2005) [hep-ex/0508025].
- [18] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **106**, 072002 (2011) [arXiv:1012.3510 [hep-ex]].
- [19] C. C. Zhang *et al.* [Belle Collaboration], Phys. Rev. D **86**, 052002 (2012) [arXiv:1206.5087 [hep-ex]].
- [20] S. J. Brodsky, A. S. Goldhaber and J. Lee, Phys. Rev. Lett. **91**, 112001 (2003) [hep-ph/0305269].
- [21] X. H. He *et al.* [Belle Collaboration], Phys. Rev. D **89**, 032003 (2014) [arXiv:1311.6337 [hep-ex]].
- [22] M. Ablikim *et al.* [BES Collaboration], Phys. Rev. Lett. **96**, 162002 (2006) [hep-ex/0602031].
- [23] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **87**, 032008 (2013) [arXiv:1211.5668 [hep-ex]].
- [24] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **107**, 182001 (2011) [arXiv:1107.1806 [hep-ex]].
- [25] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **88**, no. 9, 091502 (2013) [arXiv:1305.5333 [hep-ex]].

- [26] A. Datta and P. J. O'Donnell, Phys. Lett. B **567**, 273 (2003) [hep-ph/0306097].
- [27] M. -L. Yan, S. Li, B. Wu and B. -Q. Ma, Phys. Rev. D **72**, 034027 (2005) [hep-ph/0405087].
- [28] B. Loiseau and S. Wycech, Phys. Rev. C **72**, 011001 (2005) [hep-ph/0501112].
- [29] E. Klempt, F. Bradamante, A. Martin and J. M. Richard, Phys. Rept. **368**, 119 (2002).
- [30] S. K. Choi *et al.* [Belle Collaboration], Phys. Rev. Lett. **91**, 262001 (2003) [hep-ex/0309032].
- [31] A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **98**, 132002 (2007) [hep-ex/0612053].
- [32] RAaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **110**, 222001 (2013) [arXiv:1302.6269 [hep-ex]].
- [33] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **112**, 092001 (2014) [arXiv:1310.4101 [hep-ex]].
- [34] B. Aubert *et al.* [BaBar Collaboration], Phys. Rev. Lett. **95**, 142001 (2005) [hep-ex/0506081].
- [35] C. Z. Yuan *et al.* [Belle Collaboration], Phys. Rev. Lett. **99**, 182004 (2007) [arXiv:0707.2541 [hep-ex]].
- [36] X. L. Wang *et al.* [Belle Collaboration], Phys. Rev. Lett. **99**, 142002 (2007) [arXiv:0707.3699 [hep-ex]].
- [37] G. Pakhlova *et al.* [Belle Collaboration], Phys. Rev. Lett. **101**, 172001 (2008) [arXiv:0807.4458 [hep-ex]].
- [38] G. Pakhlova *et al.* [Belle Collaboration], Phys. Rev. D **77**, 011103 (2008) [arXiv:0708.0082 [hep-ex]].
- [39] K. Abe *et al.* [Belle Collaboration], Phys. Rev. Lett. **98**, 092001 (2007) [hep-ex/0608018].
- [40] G. Pakhlova *et al.* [Belle Collaboration], Phys. Rev. Lett. **100**, 062001 (2008) [arXiv:0708.3313 [hep-ex]].
- [41] J. P. Lees *et al.* [BaBar Collaboration], Phys. Rev. D **86**, 051102 (2012) [arXiv:1204.2158 [hep-ex]].

- [42] Z. Q. Liu *et al.* [Belle Collaboration], Phys. Rev. Lett. **110**, 252002 (2013) [arXiv:1304.0121 [hep-ex]].
- [43] J. P. Lees *et al.* [BaBar Collaboration], Phys. Rev. D **89**, 111103 (2014) [arXiv:1211.6271 [hep-ex]].
- [44] T. K. Pedlar *et al.* [CLEO Collaboration], Phys. Rev. Lett. **107**, 041803 (2011) [arXiv:1104.2025 [hep-ex]].
- [45] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **111**, no. 24, 242001 (2013) [arXiv:1309.1896 [hep-ex]].
- [46] C. -Z. Yuan, arXiv:1310.0280 [hep-ex].
- [47] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **110**, 252001 (2013) [arXiv:1303.5949 [hep-ex]].
- [48] T. Xiao, S. Dobbs, A. Tomaradze and K. K. Seth, Phys. Lett. B **727**, 366 (2013) [arXiv:1304.3036 [hep-ex]].
- [49] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **112**, no. 2, 022001 (2014) [arXiv:1310.1163 [hep-ex]].
- [50] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. **112**, 132001 (2014) [arXiv:1308.2760 [hep-ex]].
- [51] S. K. Choi *et al.* [BELLE Collaboration], Phys. Rev. Lett. **100**, 142001 (2008) [arXiv:0708.1790 [hep-ex]].
- [52] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **112**, 222002 (2014) [arXiv:1404.1903 [hep-ex]].
- [53] C. P. Shen *et al.* [Belle Collaboration], Phys. Rev. D **89**, 072015 (2014) [arXiv:1402.6578 [hep-ex]].
- [54] A. Bondar *et al.* [Belle Collaboration], Phys. Rev. Lett. **108**, 122001 (2012) [arXiv:1110.2251 [hep-ex]].
- [55] I. Adachi [Belle Collaboration], arXiv:1105.4583 [hep-ex].
- [56] I. Adachi *et al.* [Belle Collaboration], Phys. Rev. Lett. **108**, 032001 (2012) [arXiv:1103.3419 [hep-ex]].
- [57] I. Adachi *et al.* [Belle Collaboration], arXiv:1209.6450 [hep-ex].